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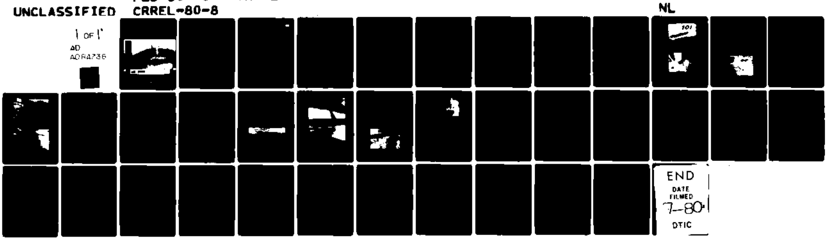

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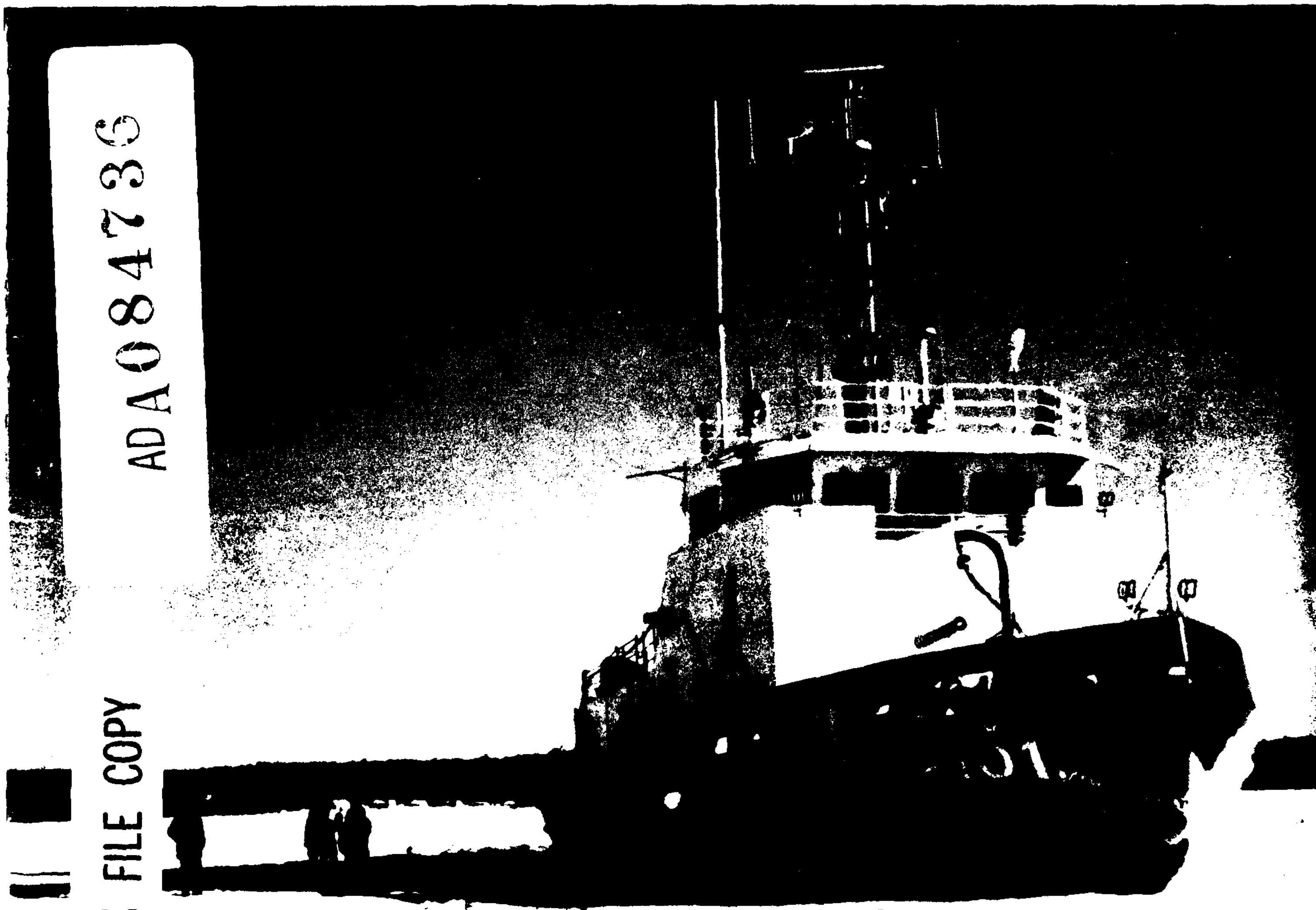
Analysis of the performance of a 140-foot Great Lakes icebreaker: USCGC Katmai Bay



Cover: *Field test of* Katmai Bay *in Lake Superior.*
(Photograph by George Vance.)

CRREL Report 80-8

Analysis of the performance of a 140-foot Great Lakes icebreaker: USCGC Katmai Bay

George P. Vance

February 1980

Prepared for
U.S. COAST GUARD
By
UNITED STATES ARMY
CORPS OF ENGINEERS
COLD REGIONS RESEARCH AND ENGINEERING LABORATORY
HANOVER, NEW HAMPSHIRE, U.S.A.

Unclassified

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
CRREL Report 80-8	AD-A084 736	

4. TITLE (and Subtitle)

ANALYSIS OF THE PERFORMANCE OF A 140-FOOT GREAT LAKES ICEBREAKER: USCGC *KATMAI BAY*

5. TYPE OF REPORT & PERIOD COVERED

6. PERFORMING ORG. REPORT NUMBER

7. AUTHOR(s)

George P. Vance

8. CONTRACT OR GRANT NUMBER(s)

U. S. Coast Guard MIPR-270099-9-91769-9B

9. PERFORMING ORGANIZATION NAME AND ADDRESS

U. S. Army Cold Regions Research and Engineering Laboratory
Hanover, New Hampshire 03755

10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS

11. CONTROLLING OFFICE NAME AND ADDRESS

U. S. Coast Guard
Washington, DC

12. REPORT DATE

February 1980

13. NUMBER OF PAGES

33

14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)

15. SECURITY CLASS. (of this report)

Unclassified

15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Field tests
Icebreakers
Ice resistance
Low friction coating
Ship bubblers

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This report presents the results of the tests on the new U.S. Coast Guard 140-ft icebreaker *Katmai Bay* (WTGB-101) in the level plate ice and brash ice in Whitefish Bay and the St. Marys River. The results indicate that the vessel can penetrate 22 in. of level freshwater ice with 2-3 in. of snow cover. It can also penetrate up to 48 in. of brash ice in a continuous mode and at least 30 in. of plate ice by backing and ramming. The installed bubbler system decreased the required power of the vessel from 10 to 30% in brash ice and 25 to 35% in level ice. The low friction coating appears to be effective in decreasing the friction factor when it remains intact; when it peels off it appears to make conditions worse than plain paint. An average dynamic friction factor of 0.15 could be used over the entire hull for these tests.

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PREFACE

This report was prepared by Dr. George P. Vance of the Ice Engineering Research Branch, Experimental Engineering Division, U.S. Army Cold Regions Research and Engineering Laboratory. The work was accomplished under U.S. Coast Guard MIPR 270099-9-91769-9B.

The manuscript of this report was technically reviewed by Guenther Frankenstein and Dr. Malcolm Mellor of CRREL.

The results presented here would not be possible without the assistance and cooperation from personnel of the U.S. Coast Guard, the U.S. Navy David Taylor Ship Research and Development Center, and CRREL, and from the captain and crew of the USCGC *Katmai Bay*. The list of names of individuals involved would be too lengthy to present here, but sincere appreciation and acknowledgment is extended to each and every one involved.

The contents of this report are not to be used for advertising or promotional purposes. Citation of brand names does not constitute an official endorsement or approval of the use of such commercial products.

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ILLUSTRATIONS

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Table 1. Daily summaries

Tuesday, 30 January 1979

Conducted continuous icebreaking tests in 12-15 in. of plate ice with 2-3 in. of snow cover without the bubbler system.

Measured surface roughness of vessel hull.

Conducted brash ice tests in shipping channel with no measurement of brash thickness.

Obtained salinity, temperature and density data.

Weather overcast with average temperature of 20°F and a 5-to 8-knot wind from 350° true north (T). Hourly weather summaries are contained in Internal Report 621.

Wednesday, 31 January 1979

Conducted continuous icebreaking tests in 13-20 in. of plate ice with and without the bubbler system.

Obtained thickness and temperature profile.

Conducted tests in brash ice in the shipping channel.

Used the impulse radar to determine thickness profiles in plate ice.

Weather overcast with an average temperature at 14°F and a 15-knot wind from 350°T.

Draft of the vessel taken in the ice was as follows:
- 10 ft 6 in. forward
- 12 ft 6 in. aft.

Thursday, 1 February 1979

Conducted brash ice tests in the shipping channel with and without the bubbler system. Impulse radar utilized to obtain brash thickness in the channel.

Attempted ramming tests in pressure ridges, but ridges not consolidated enough or strong enough to stop the vessel.

Weather partly cloudy with average temperatures of 12°F with a 12- to 14-knot wind blowing from 330°T.

Friday, 2 February, to Sunday, 4 February 1979

No tests conducted, ship was in operational status.

Monday, 5 February 1979

Held demonstrations for Coast Guard representatives. Drafts read at the dock and in the locks.

At dock: 12 ft 2 in. aft
10 ft 6 in. forward

In locks: 12 ft 7 in. aft
11 ft 0 in. forward

Tuesday, 6 February 1979

Left dock on operational mission in White Fish Bay. Conducted test in brash ice in ship channel but no thickness of brash obtained.

Conducted ad-hoc ramming tests in heavy ice enroute to USS *Munson*.

Weather overcast with average temperature of 10°F with some snow wind of 16 knots from 130°T.

Wednesday, 7 February 1979

Continued operational tasks, no tests conducted.

Thursday, 8 February 1979

Conducted brash ice tests in St. Marys River in area of Stribbley Point with and without bubbler system. Brash documented to be 2-4 ft thick.

Weather clear with average temperature of 7°F and wind of 10-14 knots from 040°T.

Friday, 9 February 1979

Conducted comparison tests with 100-ft icebreaking tug in 14 in. of ice with 5 in. of snow cover. The *Katmai Bay* progressed at about 6 knots and gained approximately 2.3 miles in 10 minutes on the 110-ft icebreaking tug.

Conducted continuous tests in approximately 10 in. of ice with 3 in. of snow cover. Ice was under heavy pressure from prevailing wind.

Made hull roughness measurements.

Weather clear with average temperature -10°F and wind of 8-14 knots from 130°T.

Saturday, 10 February 1979

Conducted brash tests in St. Marys River in approximately 4 ft of brash with and without bubbler system.

Conducted continuous tests in 17 in. of plate ice with 12 in. of snow cover in anchorage area. Plate ice had incipient cracks due to vessel traffic and thermal effluent.

Conducted friction tests on ice and steel plates coated with Inerta 160 or not coated.

Weather clear and bright with average temperature of 0°F and wind of 6 knots from 270°T.

Monday, 12 February 1979

Conducted friction tests on ice. Weather clear and bright-similar to Saturday, 10 February.

Testing for Phase I completed.

Tuesday, 13 March 1979

Conducted tests in brash ice in St. Marys River with and without bubbler system. Very good documentation of brash thickness.

Weather clear with average temperature rather high at 40°F and 8-knot wind from 130°T.

Wednesday, 14 March 1979

Started to conduct turning tests in brash when steering casualty experienced requiring two days of repair work.

Thursday, 15 March 1979

Conducted friction tests on uncoated steel plate at dock. Weather clear and sunny with average temperature of 17°F and wind of 8 knots from 290°T.

Friday, 16 March 1979

Conducted friction tests at dock side with steel plate coated with Inerta 160.

Weather clear and bright with average temperature of 40°F with a 4-knot wind from 195°T.

Saturday, 17 March 1979

Conducted ramming tests in White Fish Bay in plate ice 22-30 in. thick with 3-4 in. of snow cover.

Obtained roughness data on the ship's hull for the final phase of the tests.

Weather clear with an average temperature of 42°F and a wind of 8-12 knots from 150°T.

ANALYSIS OF THE PERFORMANCE OF A 140-FOOT GREAT LAKES ICEBREAKER: USCGC KATMAI BAY

George P. Vance

INTRODUCTION

Late in 1978 the first of a class of new icebreaking tugs, the USCGC *Katmai Bay* (WTGB-101) was delivered to the U.S. Coast Guard for deployment on the Great Lakes. The Coast Guard contracted the assistance of the Naval Ship Research and Development Center (NSRDC) and the U.S. Army Cold Regions Research and Engineering Laboratory (CRREL) to conduct extensive tests of the vessel operating in ice.

The ultimate objective of the tests was to determine the operational capabilities of the vessel. The Coast Guard Center coordinated the testing and obtained data pertaining to the motion of the vessel, i.e. role, pitch, heave, etc. NSRDC obtained information pertaining to the ship mechanical systems, i.e. shaft horsepower (SHP) thrust, vibration and hull stresses. CRREL was responsible for obtaining ice property and friction data and for conducting the icebreaking capability analysis.

The ice property data are reported in Vance (1980) with thicknesses and strengths in CRREL Internal Report 621. The present report delineates the operational characteristics of the *Katmai Bay* in level plate ice and brash ice. The tests were conducted in Whitefish Bay of Lake Superior and in the upper reaches of the St. Marys River during February, March, and April of 1979.

Table 1 provides a brief review of the type of tests conducted each day of the test period and delineates the general weather conditions during the tests.

ROUGHNESS AND FRICTION MEASUREMENTS

The roughness of the hull plating was measured at various locations on the hull with a Taylor-Hobson Surtronic 3 Surface Profilometer, which measured the center line average roughness in a specific location (see Fig. 1). Several readings were made in each location and are reported in Internal Report 621. Although no exact correlation has been made between roughness and the coefficient of friction, the trend of increasing friction with increasing roughness has been shown (e.g. Calabrese and Ling 1978).

There were essentially four different surfaces exposed to the ice and snow (see Fig. 2). These surfaces were: 1) the special low friction hull coating Inerta 160*, 2) the black paint of the hull above the waterline, 3) the hull surface where the Inerta 160 had peeled completely away and 4) the hull surface where the black hull paint had peeled or been worn away. The difference in roughness between the various surfaces was significant and is shown in Figure 3. The Inerta 160 had the lowest average center line average (CLA) roughness of 55 μin. The surface with the largest roughness was the surface where the Inerta 160 had peeled away. The average CLA roughness in this area was 450 μin., some eight times rougher than the Inerta 160 surface. The extremely high roughness of this surface can be attributed to the fact that the metal surface is specially prepared for the application of the Inerta 160

* Inerta 160, distributed by International Paints, Inc., is a two-part solventless low-friction, high-bonding-strength epoxy coating.

Figure 1. Hull plating condition on port bow of Katmai Bay.

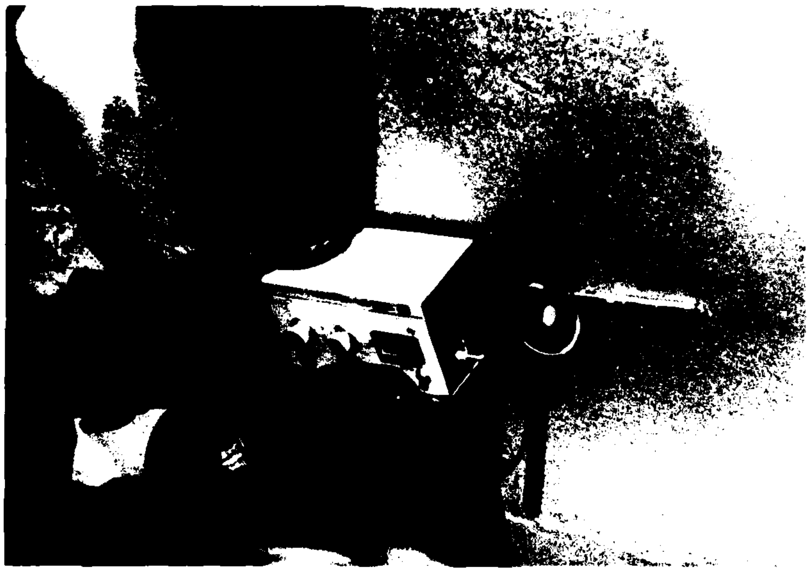

Figure 2. Conducting roughness measurements on Katmai Bay.

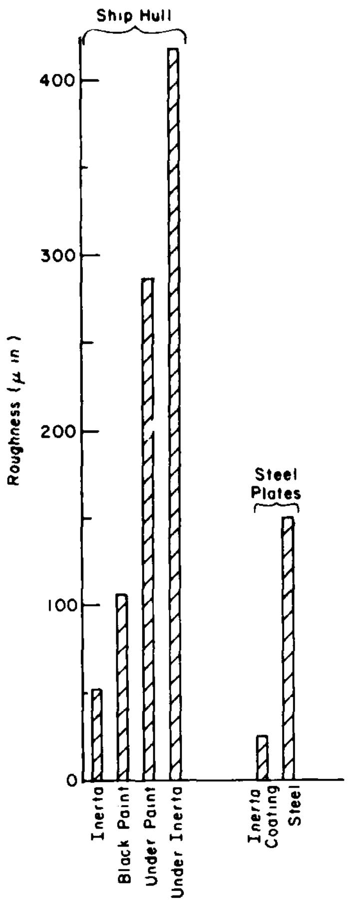

Figure 3. Roughness comparisons.

Figure 4. Conducting roughness comparisons on Inerta 160 coated steel plate.

Table 2. Friction coefficients

	Feb. 1979	March 1979
Dynamic		
1 Inerta-ice with screw jack*	0.020	0.015
2 Inerta-ice with winch†	0.045	0.030
3 Inerta-water with screw jack	0.060	—
4 Inerta-snow with screw jack	0.145	0.115
5 Inerta-snow with winch	—	0.085(low)
1 Steel pl-ice with screw jack	0.050	0.150(high)
2 Steel pl-ice with winch	0.071	0.100
3 Steel pl-water with screw jack	0.100	—
4 Steel pl-snow with screw jack	0.165	0.165
5 Steel pl-snow with winch	—	0.170
Static		
1 Inerta-ice with screw jack	0.037	0.085
2 Inerta-ice with winch	0.080	0.185
3 Inerta-water with screw jack	0.135	—
4 Inerta-snow with screw jack	0.200	0.240
5 Inerta-snow with winch	—	0.250
1 Steel pl-ice with screw jack	0.080	0.215
2 Steel pl-ice with winch	0.201	0.310
3 Steel pl-water with screw jack	0.120	—
4 Steel pl-snow with screw jack	0.480(high)	0.250
5 Steel pl-snow with winch	—	0.410(high)

*Motor-driven screw jack that moved at 0.252 ft/sec
†Motor-driven cable winch that moved at 0.52 ft/sec

and is very carefully sandblasted to bare metal. The bond between the Inerta 160 and the metal is supposedly made by the Inerta 160 penetrating deeply and completely into the metal pores. When the bond does fail, the Inerta 160 pulls off completely and leaves bare metal with no rust or pigment fragments filling in the pores.

In addition, friction tests were carried out on two steel plates (Fig. 4). One plate was coated with the Inerta 160 and another plate was plain steel with some degree of rust. The average CLA roughness values of the plates are shown in Figure 3. The plate measurements indicated a smoother surface than that of the hull itself, mainly due to the fact that the plates, although coated in a similar fashion, had not experienced the operational abuse of the hull plating. The results of the extensive friction tests are reported in Vance (1980) and are summarized in Table 2. The trend indicates higher friction factors with increased roughness and increased velocity.

For the purpose of this report it is difficult to state a specific dynamic coefficient of friction to apply to the vessel for the case at hand. The exact ice condition and lubrication factors varied greatly during the test; however, one could suggest the following values of the dynamic friction coefficient based on observations and the tests conducted:

Smooth hull (Inerta 160) well-lubricated	0.05
Smooth hull (Inerta 160) not well-lubricated (snow)	0.10 to 0.125
Rough hull (old steel) well-lubricated	0.125 to 0.150
Rough hull (old steel) not well-lubricated (snow)	0.175 to 0.200

Due to the fact that the Inerta 160 was peeling and there was almost always a snow cover, an average value of 0.15 was used in the calculations for these ship tests.

LEVEL PLATE ICE PERFORMANCE

Level plate ice tests were conducted on four different occasions, three of which were in Whitefish Bay with ice thicknesses of approximately 12, 14 and 16 in. and 3-6 in. of snow cover. The fourth test was conducted in the St. Marys River anchorage area between buoys 79 and 83 where the ice measured 27 in. and had 12 in. of snow cover. Since these values exceeded the design capability of the vessel by some 20 to 25%, the ice was investigated further and it was found that the ice was not really homogeneous plate ice but plate ice that had been cracked and partially refrozen. Aerial photos indicated that the icebreaker *Mackinaw* had been in the anchorage area during the week of 18 January, some 21 days before the tests were conducted (see Figs. 5 and 6). Therefore, the data from these tests were not included in the analysis but are available in Internal Report 621.

The data for the plate ice tests are also contained in their entirety in Internal Report 621. Temperature measurements indicate that the flexural strength of the ice can be estimated to vary from 12,000 to 15,000 lbf/ft^2 (Vance 1980). Figures 7-10 depict the results for various thicknesses, plotting SHP vs velocity with and without the bubbler system in operation (σ = flexural strength of the ice).

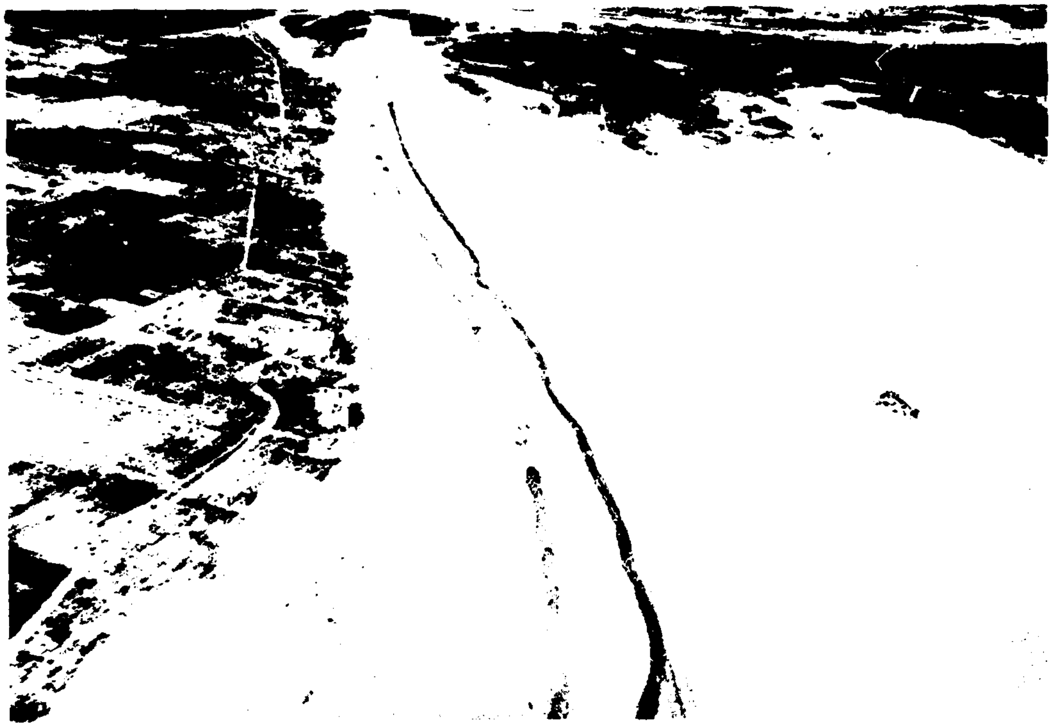

Figure 5. Aerial view looking upstream showing ice conditions and steamer track in courses 3 and 4 of Little Rapids Channel — Six Mile Point, left foreground, 18 January 1979, 1200 to 1400 hr.

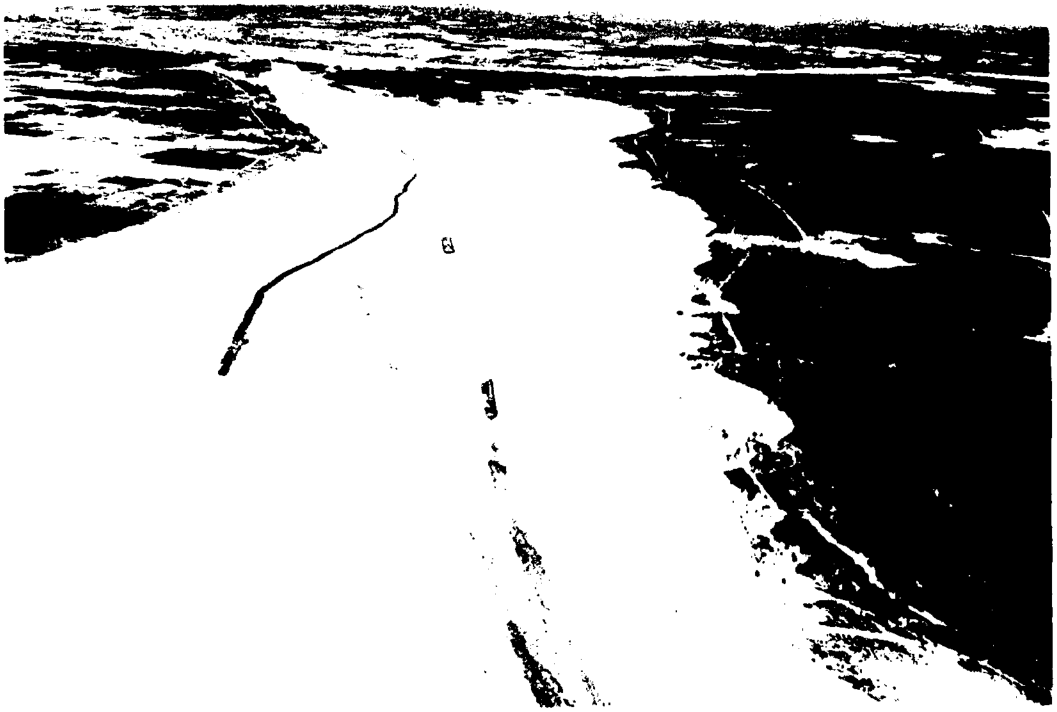

Figure 6. Aerial view looking upstream showing ice conditions and steamer track in Lake Nicolet-Nine Mile Point in right foreground, 18 January 1979, 1200 to 1400 hr.

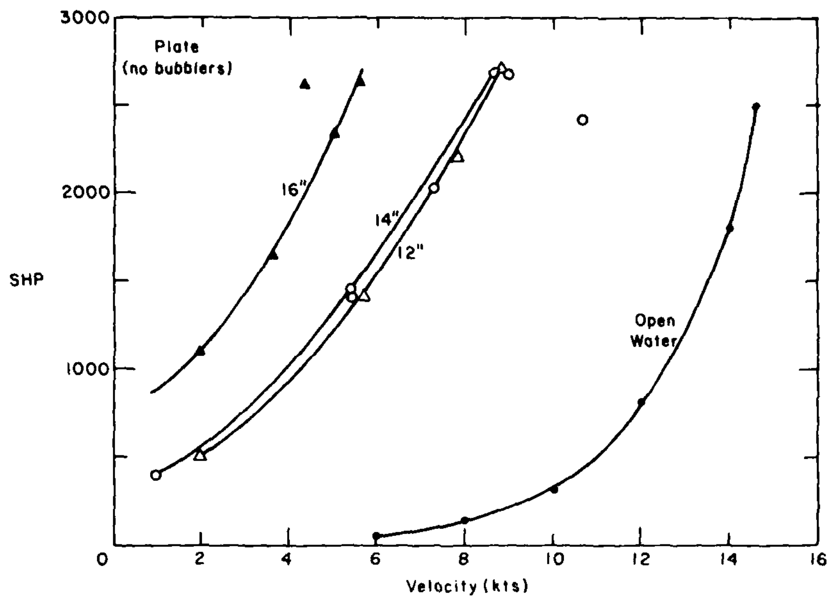

Figure 7. Shaft horsepower vs velocity for plate ice with no bubblers in operation (3 to 5 in. of snow cover, σ = 12 to 15 kips/ft²).

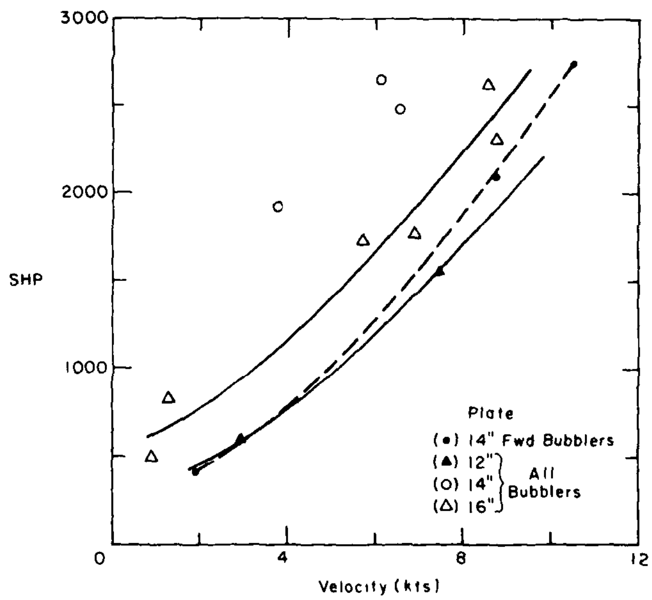

Figure 8. Shaft horsepower vs. velocity in plate ice with all bubblers in operation (3 to 5 in. of snow cover, σ = 12 to 15 kips/ft²).

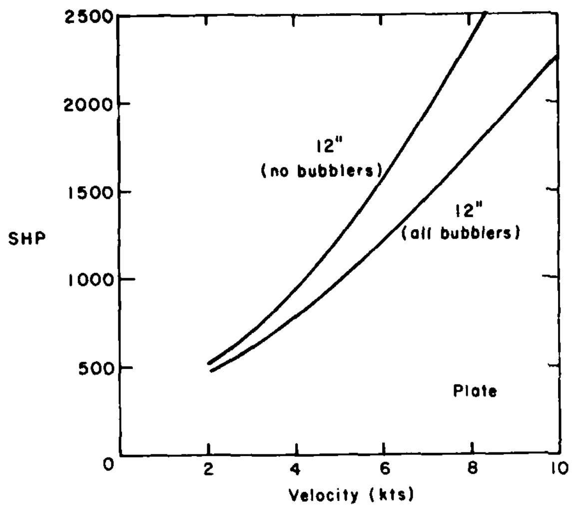

Figure 9. Shaft horsepower vs velocity in plate ice with 3 to 5 in. of snow cover, with aft bubblers or no bubblers in operation.

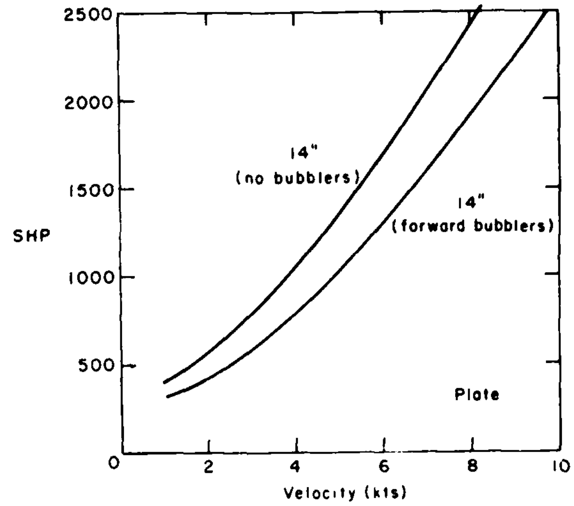

Figure 10. Shaft horsepower vs velocity in plate ice with 3 to 5 in. of snow cover with forward bubblers or no bubblers operating.

Figure 7 depicts the variation of power with thickness with no bubblers activated. The ice-free open water power curve is taken from West (1975). A definite relationship between thickness, power and velocity can be noted. The large increase in required power for the 16-in. ice is due to a significant prevailing wind during that particular test day. The data points that appear to be outliers are due to the difficulty of obtaining homogeneous conditions for each run because snow thickness varied considerably and minor pressure ridges or hummocks in the ice were present in some runs. Specific analytical relationships relating environmental parameters to resistance will be developed in the analysis section of this report.

Figure 8 depicts the power vs velocity curves with the bubbler system activated. The data here suffer from the same inconsistencies as those in the no bubbler case. Several of the 14-in. data points with all bubblers in operation appear to be rather high compared to the 16-in. data points. All of these higher points were taken on 9 February in an area where the ice flexural strength reached the maximum recorded for all tests, some 15,660 lbf/ft^2.

Figure 9 and Table 3 are comparisons of the resistance in 12 in. of level ice with 3-5 in. of snow cover. The curves were extracted from the previous two curves. The curves indicate a 10 to 25% decrease in required power, i.e. 50 HP at 2 knots and 575 HP at 8 knots, with the bubbler system activated. The decrease in required power is compared to 260 HP required to operate the bubbler system with the forward or all the units operating and 315 HP with the aft systems operating.

Figure 10 and Table 4 compare the required power in 14 in. of ice with 3-5 in. of snow cover. The average decrease in required power is 24%. Again we see that, although the decrease at 2 knots is some 25%, we are only gaining 145 HP compared to 260 HP being utilized by the bubbler system.

The comparisons in Figure 11 and Table 5 for 16 in. of ice indicate the most impressive power savings, an average of 35%. This is primarily due to the weather conditions on the day these tests were conducted. There was a prevailing wind that created a significant ice pressure force. Although no quantitative measurements were made, this was the only day that the track closed

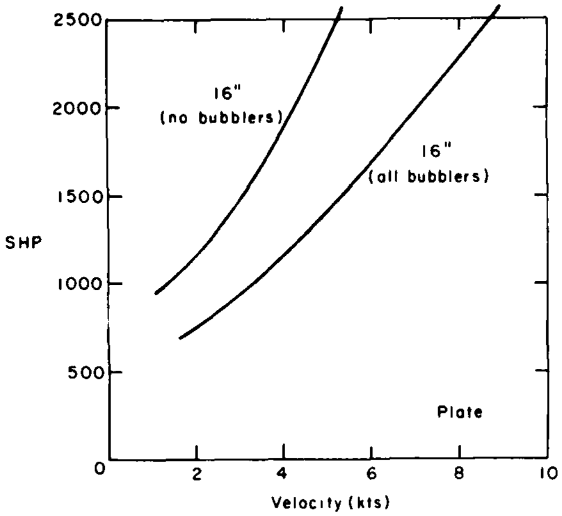

Figure 11. Shaft horsepower vs velocity in plate ice and 3 to 5 in. of snow cover–comparison of performance with all bubblers operating or no bubblers.

Table 3. Bubbler comparison for 12-in. plate ice and 3 to 5 in. of snow.

Vel (kt)	*SHP (no bub)*	*SHP (all bub)*	*ΔSHP/ %diff*	*HP Bub*	*HP Net*
2	500	450	50/10	260	-210
4	930	715	215/23	260	-45
6	1550	1200	350/23	260	+90
8	2275	1700	575/25	260	+315

Table 4. Bubbler comparison for 14-in. plate ice and 3 to 5 in. of snow

Vel (kt)	*SHP (no bub)*	*SHP (fwd bub)*	*ΔSHP/ %diff*	*HP Bub*	*HP Net*
2	570	425	145/25	260	-115
4	1050	780	270/26	260	+10
6	1680	1290	390/23	260	+130
8	2440	1900	540/22	260	+280

Table 5. Bubbler comparison for 16-in. plate ice and 3 to 5 in. of snow with intense pressure.

Vel (kt)	*SHP (no bub)*	*SHP (all bub)*	*ΔSHP/ %diff*	*HP Bub*	*HP Net*
2	1150	700	450/39	260	+190
4	1850	1230	620/34	260	+360
5	2350	1400	950/40	260	+690

immediately behind the vessel. During other test runs on other days, the track would be clear of brash ice for at least one or two ship lengths. Although it may appear that the decrease in required power with the bubbler system in operation is due only to the lubrication of the hull by the water brought up with the air bubbles, this particular phenomenon may not be the only mechanism increasing the effectiveness of the vessel. The results of the resistance computation in the analysis section indicate that there may be a secondary phenomenon of ice displacement that may be affecting the efficiency of the propulsion system. This phenomenon will be discussed in detail in *Analysis of the Data*.

BRASH ICE PERFORMANCE

As indicated in the daily summaries, brash ice tests were conducted on six different occasions both in Whitefish Bay and the St. Marys River. Environmental conditions varied considerably in both areas. Tests on 31 January, 1 February and 6 February were conducted in the ship channel southeast of Isle Parisienne enroute to plate ice tests or enroute to an operational mission, and the thickness of the brash ice was not measured but only estimated from the bridge of the vessel or from radar records obtained on 1 February. The results of these tests therefore must be reviewed with caution. Due to the variation in the brash ice conditions in the ship channel and the absence of specific measurements in these particular tests, there is considerable scatter in the data, particularly on 6 February, when it appears that the vessel performed more effectively without the bubbler system than it did with the bubbler system.

The tests conducted on 8 and 10 February and 13 March were conducted under more controlled conditions and reflect the expected performance of the vessel with and without the bubbler system activated. These tests definitely show the benefit of the bubbler system; however, there were insufficient data to distinguish the relative contribution of the forward and aft bubbler systems.

Figures 12 and 13 are views of the ship channel in Whitefish Bay between Gros Cap Reef light and Birch Point. The variation in brash conditions can easily be seen, with the darker areas indicating open water and the lighter areas indicating tightly packed brash.

Figure 12. Aerial view looking upstream showing ice condition and steamer track in Whitefish Bay—Gros Cap Reef light, right foreground, Isle Parisienne right background, 28 January, 1300 to 1500 hr.

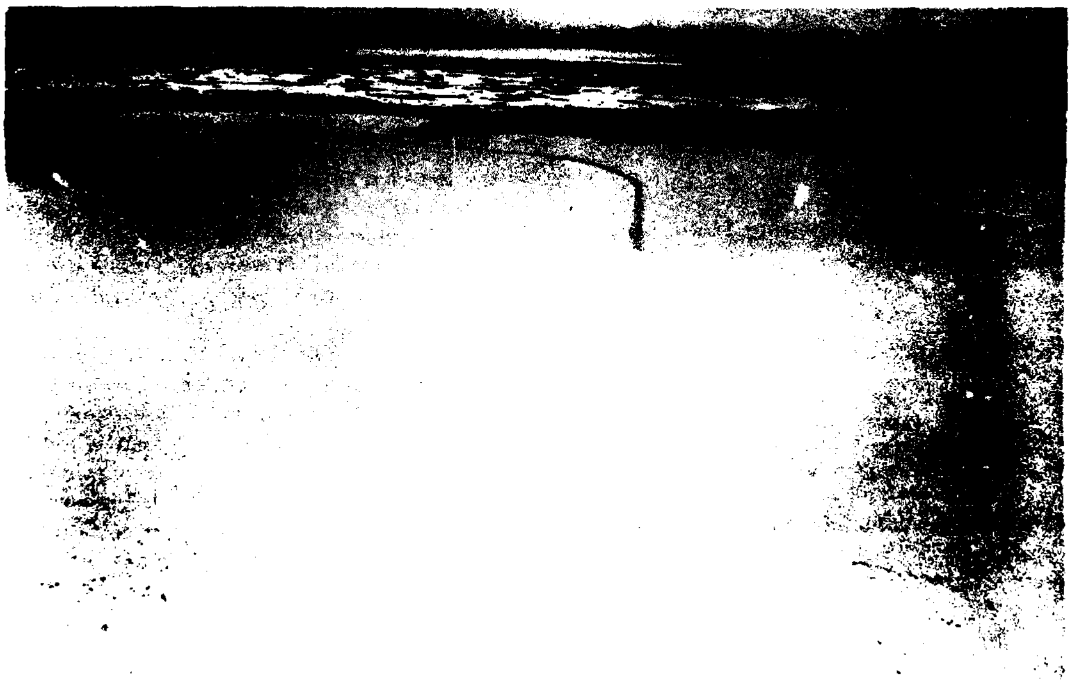

Figure 13. View looking downstream showing ice conditions and steamer track in Birch Point Course, 28 January 1979, 1300 to 1500 hr

Figure 14. Aerial view looking upstream showing ice conditions and steamer track in angle 5-6 and course 5 of Middle Neebish Channel—Neebish Island is in foreground, 9 February 1979, 1200 to 1400 hr.

Figure 15. Aerial view looking upstream showing ice conditions and steamer track through Lake Nicolet with Nine Mile Point in right foreground, 9 February 1979, 1200 to 1400 hr.

Figures 14 and 15 are views of the ship track in Middle Neebish Channel and Lake Nicolet. The consistency of the brash can be seen in Figure 16. Figures 16 and 17 indicate that the brash ice in the channel during tests on 8 and 10 February was packed so tightly one could walk out and measure the thickness immediately after the passage of the vessel. This was not the case for the tests on 13 March, where the channel was completely filled but was not packed to the point where one could walk on it after passage of the vessel.

Figure 18 and Table 6 depict the results of the runs conducted on 31 January and 1 February. The tests were conducted with the bubbler inactive, fully active and with only the forward bubbler system operating. These tests indicate a decrease of only 12-14% in required power when the bubbler system is activated. The tests also indicate questionable benefit at low speeds. The varied results can be attributed to the variation in conditions and the lack of documentation of these variations. In addition, open water tests with the bubbler system activated and the propeller not turning indicated that a reverse thrust developed which was capable of propelling the vessel rearward at approximately one knot.

Figure 19 and Table 7 represent the results of the tests on 6 February. It is obvious that conditions changed sufficiently as the vessel progressed down the channel to have a significant effect on the required power. Clearly more power was required to propel the vessel with the bubbler system active than with the system inactive.

Figure 20 is an indication of the performance of the vessel in 42 to 60 in. of brash ice. These tests were conducted in the St. Marys River with the vessel transiting back and forth in the ship track.

Figure 21 and Table 8 depict the results of the tests conducted on 10 February in the St. Marys River, which are the most reliable of the brash ice tests. The brash thickness was very well documented and the vessel transited back and forth in the ship channel. These results indicate a 30 to 50% decrease in required power when utilizing the bubbler system.

Figure 22 and Table 9 depict the results of the tests conducted on 13 March, and although the thickness of the brash was well documented, the brash was not packed sufficiently to permit measurements in the middle of the ship channel.

Figure 16. Brash ice in St. Marys River.

Figure 17. Brash ice measurements in St. Marys River.

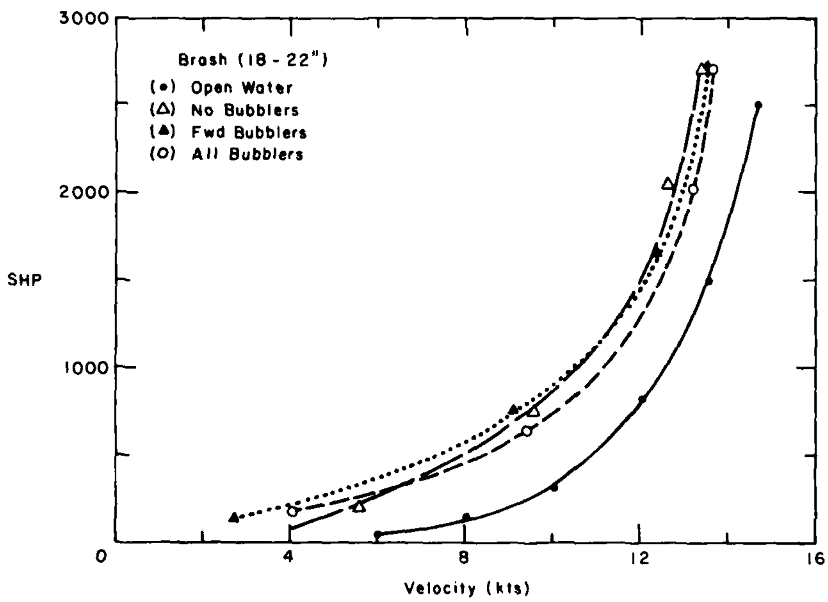

Figure 18. Shaft horsepower vs velocity in brash ice, 31 January–1 February 1979.

Table 6. Bubbler comparison in 18- to 22-in. brash ice, 31 January and 1 February 1979.

Vel (kt)	SHP (no bub)	SHP (fwd bub)	ΔSHP %diff	HP Bub	HP Net	SHP (all bub)	ΔSHP %diff	HP Bub	HP Net	All-Fwd
4	75	225	150/200	260	-410	180	105/140	260	-365	45/20
6	270	375	105/40	260	-365	270	0	260	-260	105/28
8	510	590	80/16	260	-340	450	60/12	260	-200	140/24
10	870	900	30/4	260	-290	750	120/14	260	-140	150/17
12	1500	1490	10/1	260	-250	1300	200/13	260	-60	190/13

Table 7. Bubbler comparison in approximately 18-in. of varying brash ice, 6 February 1979.

Vel (kt)	SHP (no bub)	SHP (all bub)	ΔSHP/ %diff	HP Bub	HP Net
4	75	270	195/260	260	-455
6	450	660	210/47	260	-470
8	850	1090	240/28	260	-500
10	1300	1550	250/19	260	-510
12	1800	2110	310/17	260	-570

**All bubblers

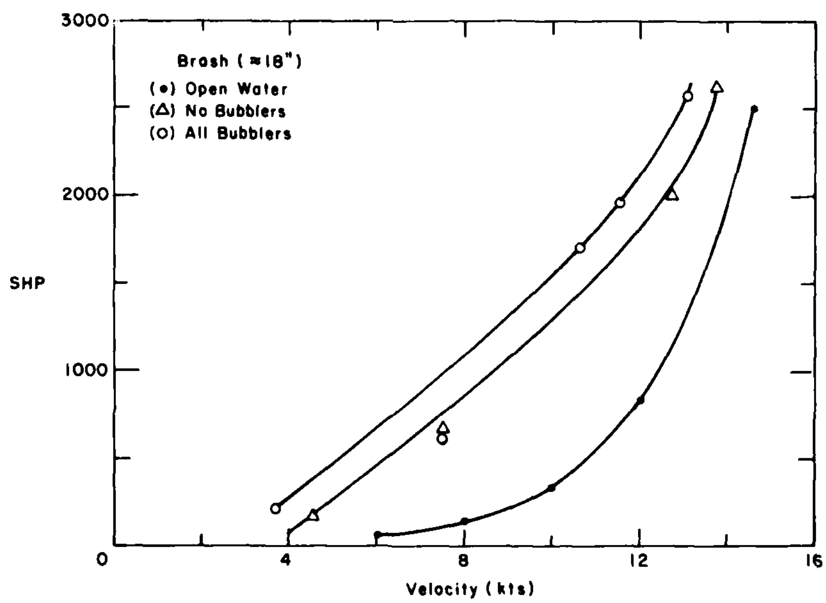

Figure 19. Shaft horsepower vs velocity in approximately 18 in. of brash ice, 6 February 1979.

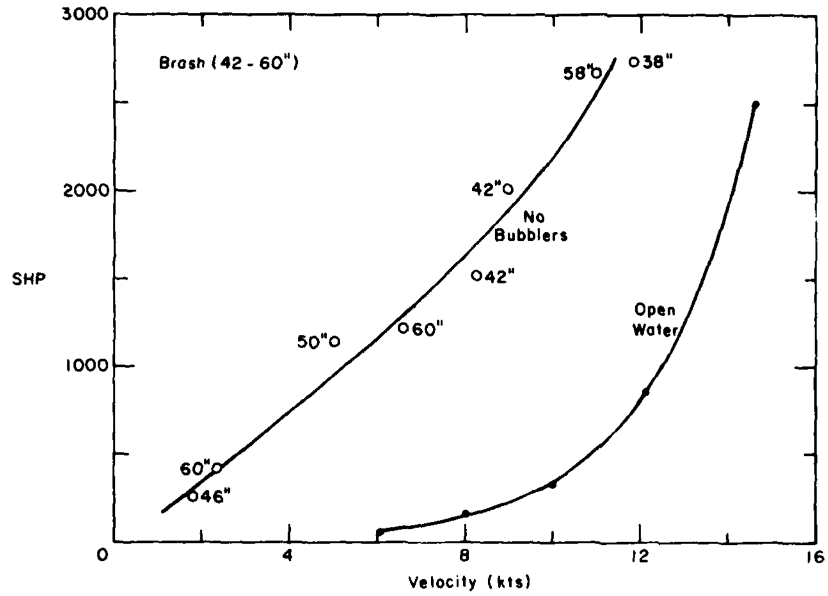

Figure 20. Shaft horsepower vs velocity for 42 to 60 in. of brash ice, 8 February 1979.

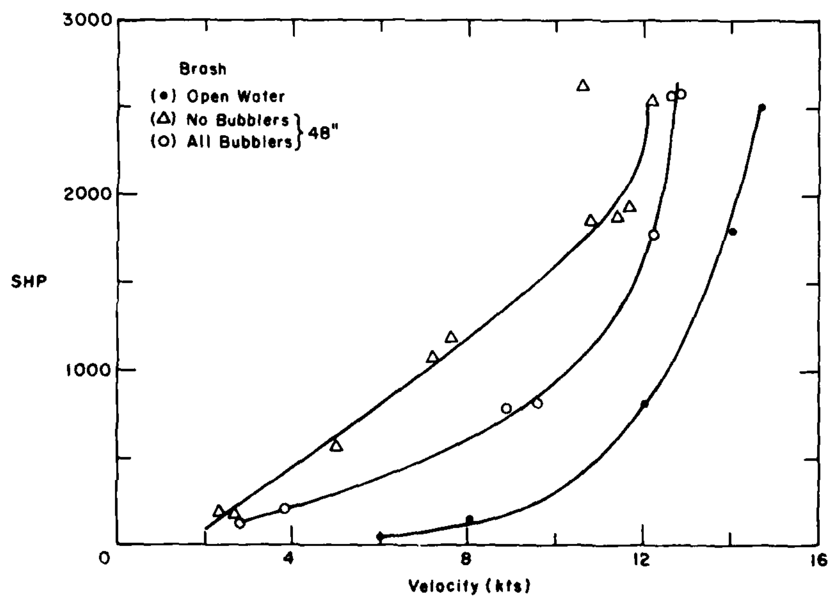

Figure 21. Shaft horsepower vs velocity for 48 in. of brash ice, 10 February 1979.

Table 8. Bubbler comparison in 48-in. brash ice, 10 February 1979.

Vel (kt)	SHP (no bub)	SHP (all bub)	ΔSHP %diff	HP Bub	HP Net
4	450	225	225/50	260	- 35
6	810	400	410/51	260	+ 150
8	1190	610	580/49	260	+ 320
10	1610	950	660/41	260	+ 400
12	2350	1650	700/30	260	+ 440

Table 9. Bubbler comparison in 39- to 45- in. brash ice, 13 March 1979.

Vel (kt)	SHP (no bub)	SHP	ΔSHP/ %diff	HP Bub	HP Net	SHP (all bub)	ΔSHP/ %diff	All/Aft	All/Fwd	Aft/Fwd
6	600	400*	200/33	260	- 60	460	140/23	65/12	(60/15)	(125/24)
8	825	800*	25/3	260	-235	750	75/9	75/9	50/6	(25/3)
10	1200	1250*	(50/4)	260	-210	1100	100/8	175/14	150/12	(25/2)
12	1700	1925*	(225/13)	260	-35	1600	100/6	225/12	325/17	100/6
6		525†	75/13	315	-240					
8		825†	0	315	-315					
10		1275†	(75/6)	315	-240					
12		1825†	(125/7)	315	-190					
6		460**	140/23	260	-120					
8		750**	75/9	260	-185					
10		1100**	100/8	260	-130					
12		1600**	100/6	260	-130					

*Forward bubbler
†Aft bubbler
**All bubblers

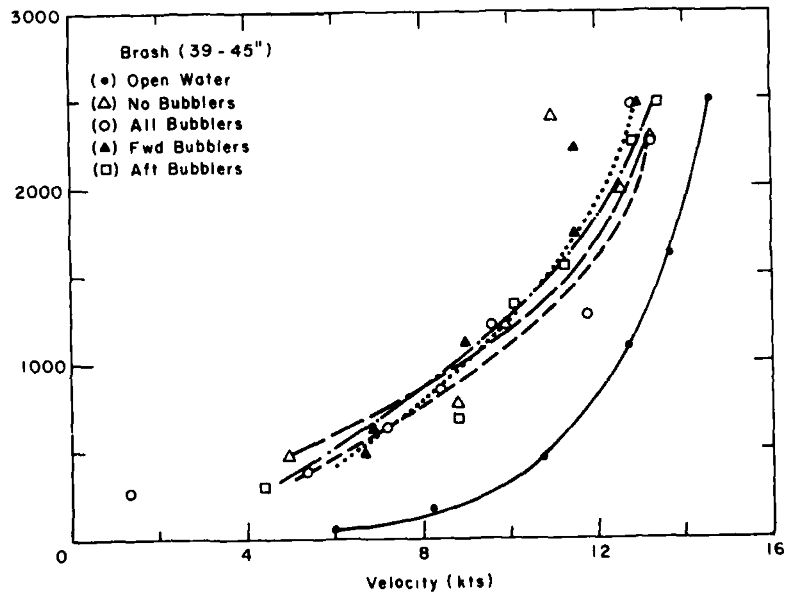

Figure 22. Shaft horsepower vs velocity for 39 to 45 in. of brash ice, 13 March 1979.

This accounts for the inconsistent evaluation of the forward and aft bubbler system working independently. However, the trend indicates a 6 to 23% decrease in required power with the bubbler system operating.

RAMMING ICEBREAKING PERFORMANCE

One of the objectives of the field tests was to evaluate the *Katmai Bay* in the ramming icebreaking mode to determine the vessel's capability to penetrate pressure ridges. The original plan was to utilize the evaluation techniques recommended by Makinen (1975). However, there were no substantial pressure ridges available during the test period. An attempt was made to penetrate ridges on 1 February, but the ridges were so insignificant that the vessel penetrated them with little or no trouble. The vessel parameters measured and pertinent ice data are presented in Internal Report 621 and the details of the ice conditions are noted in Vance (1980). There are insufficient data to make any comprehensive analysis.

On 6 February the vessel was transiting a field of brash ice on an operation mission and had to resort to backing and ramming to make continuous progress. Although no comprehensive data were collected, radar ranges were utilized to estimate the ship's progress and ice conditions were estimated from the bridge. The plotted data in Figure 23 are an indication of the acceleration distances required to reach specific impact velocities. The data in this curve have considerable scatter, which is to be expected, considering that they were obtained while in an operational mode. However, the general trend is similar to that shown in Figure 24, the data for which were collected under controlled conditions.

On 17 March tests were conducted in Whitefish Bay in plate ice that varied from 22 to 33 in. in thickness. Extensive data were collected with and without the bubbler system activated. It was evident that the vessel could not penetrate the plate ice with snow cover in a continuous fashion, although the penetration distances in runs

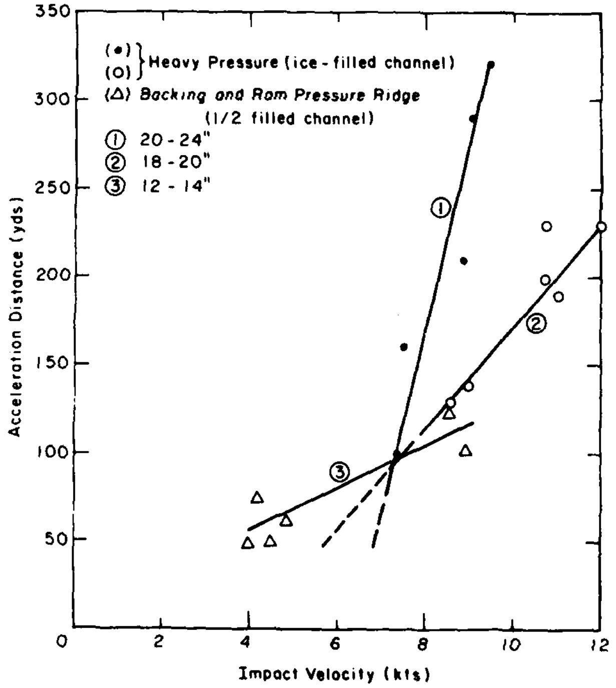

Figure 23. Acceleration distance in ice-filled channel at full power with no bubblers operating, 6 February 1979.

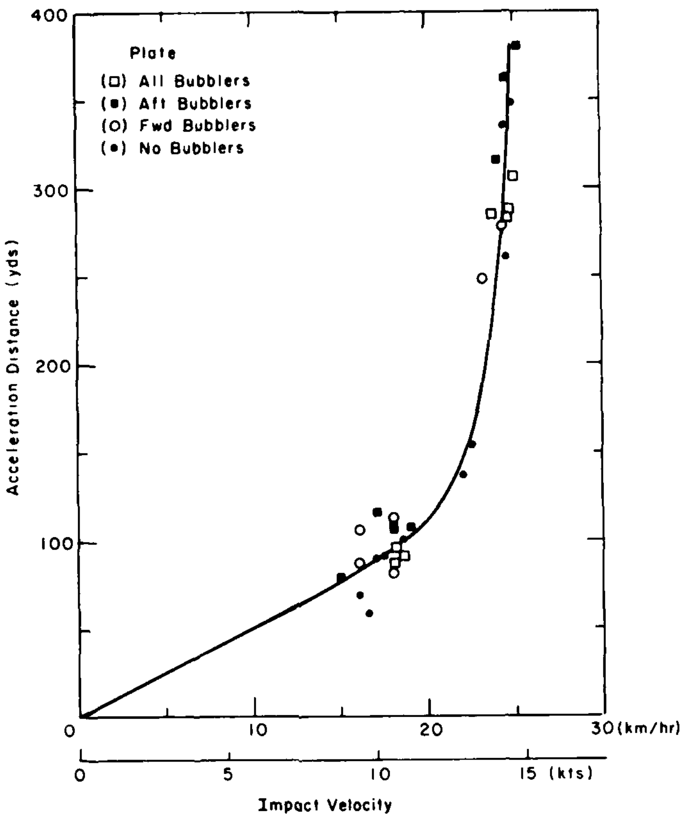

Figure 24. Acceleration distance in a channel in plate ice, 17 March 1979.

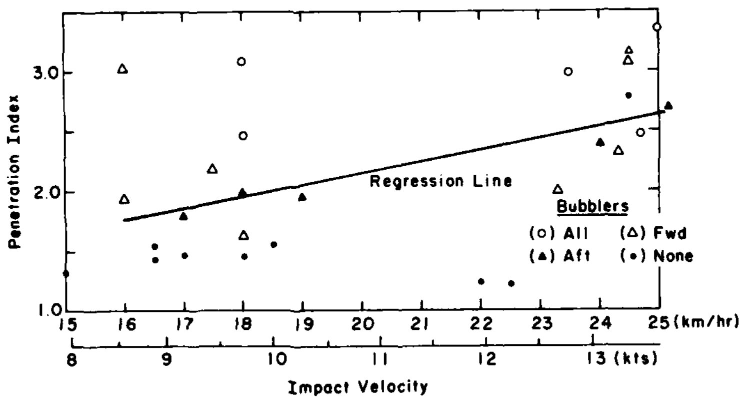

Figure 25. Penetration index vs impact velocity, 17 March 1979.

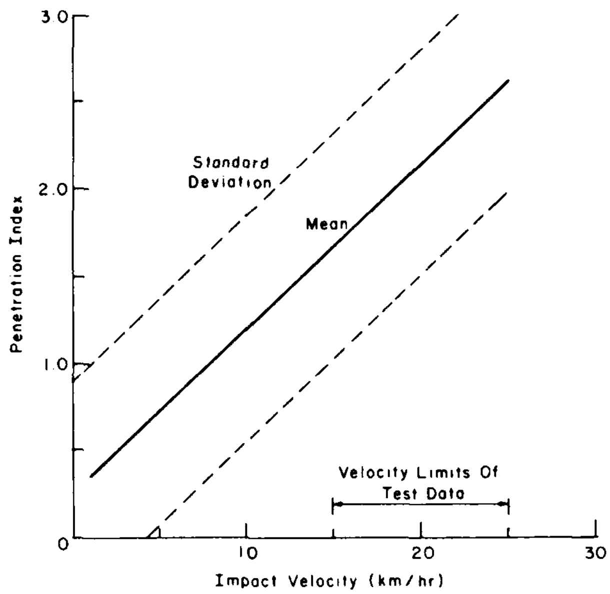

Figure 26. Computed penetration index vs impact velocity in 22 to 30 in. of ice and 2 to 3 in. of snow where PI = 0.095 (IMVEL) +0.255, R = 0.505, σ = 0.65 and PI_{AVG} = 2.17.

6203 and 6405 exceeded 90 yards (about 2 ship lengths), and comments from observers on the vessel's bridge indicated that the vessel was just short of moving continuously through the ice sheet.

The data presented in Internal Report 621 indicate that the vessel can ram through ice 33 in. thick. The distance that the vessel required to obtain a specific impact velocity is shown in Figure 24 where it can be seen that the bubbler system contributes very little in the ramming mode. It is also evident that the impact velocity remains fairly constant after accelerating for about 2.5 to 3.0 ship lengths; i.e. there is no gain in impact velocity by backing up more than 100-150 yards.

The data also provide some insight into how far the vessel will penetrate a certain thickness of ice at a specific impact velocity. Figure 25 is a plot of a penetration index (PI) vs impact velocity. The PI is an empirical dimensional parameter and defined in this report as the penetration distance in yards times the ice thickness in inches divided by 1000. Thus if an operator desired to determine how far he could penetrate 26 in. of ice by impacting at 10 knots with or without bubblers operating, he would obtain the PI from Figure 24 (i.e. 2.0) and multiply this by 1000 and divide by 26 to obtain 76 yards. Figure 26 is a plot of the PI extrapolated beyond the range of the measured data. The regression equation for the penetration index can readily be used in a computer algorithm to predict the outcome of various mission profiles. One should note the PI's presented here are valid only for the 140-ft icebreakers.

It should be noted that all tests were conducted at full power and impact velocity was varied by changing impact distance. Broken ice was always present in the channel.

ANALYSIS OF THE DATA

Propulsion efficiency in ice

The data presented prior to this section have been given in terms of the power measured at the shaft within the ship itself. Although this

power represents that required to be developed by the propulsion machinery, it does not indicate how efficiently the power delivered is being utilized and where the specific losses may be occurring.

If we consider the power distribution in a screw propelled vessel as shown in Figure 27, we see that there may be losses when passing through the vessel's skin and bearings, losses from less-than-ideal flow to the propeller, losses due to inefficiency of the propeller, and losses due to the interaction of the hull and the propellers. We can define these interactions as follows:

EHP/THP = hull efficiency (1)

THP/DHP' = propeller efficiency (2)

DHP'/DHP = relative rotative efficiency (flow efficiency) (3)

DHP/SHP = shaft transmission efficiency (4)

EHP/SHP = propulsive coefficient (5)

where EHP = effective horsepower required to obtain desired speed after all losses are taken into consideration
THP = thrust horsepower available aft of the propeller
DHP' = horsepower delivered to the propeller considering losses due to flow into propeller
DHP = horsepower delivered to the propeller
SHP = horsepower available at the shaft at the main engine
PC = propulsive coefficient.

These losses are well-documented for vessels operating in ice -free waters. For the 140-ft icebreaker model tests conducted by NSRDC and reported in West (1975), a $PC = 0.565$ is indicated over a speed range of 6 to 12 knots, and then falls off to 0.5 at 14 knots. The propeller efficiency is dependent on propeller loading and the vessel's speed of advance. The characteristics of the model propeller used by NSRDC are shown in Figure 28.

The average relative rotative efficiency is given as 1.02 and the average hull efficiency is given at 1.08. The hull efficiency can be defined as:

$$EHP/THP = (1-t)/(1-w) \quad (6)$$

where t = the ice-free thrust deduction factor [$t = (T-R)/T$]
w = the ice-free wake factor [$w = (V-V_a)/V$]
V = the vessel velocity
V_a = the velocity seen by the propeller
T = the shaft thrust
R = the ship's resistance.

The thrust deduction factor in ice-free water can be simply explained as the difference in the pressure field at the stern with and without the propeller as shown in Figure 29. Curve A indicates the pressure distribution with the propeller, curve B indicates the pressure gradient due to the propeller alone, and curve C indicates the combined pressure gradient. This reduction in pressure at the stern increases the resistance and this increase must be overcome by a fraction t of the propeller thrust T.

In ice the situation is altered considerably. The ice floes not only disturb the water flow but also interact with the propeller itself. Just what effect this interaction has is difficult to determine at this time, but Figures 30-34 show the predicted PC of the *Katmai Bay* operating in various ice conditions with and without the bubbler. The predictions were based on the assumption that the thrust deduction factor t was identical to that of the ice-free water case. Thus the resistance was calculated from the shaft thrust using the following relationship:

$$R = T(1-t) \quad (7)$$

The PC was then determined from the relationships:

$$EHP = RV/550 \quad (8)$$

$$PC = EHP/SHP. \quad (9)$$

In the above equations, SHP was calculated from the measured torque and RPM of the shaft, the thrust was measured on the shaft, and the velocity was measured with mini-range transponders. The only uncertainty comes in the

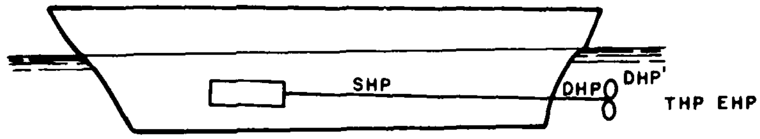

Figure 27. Distribution of power in a screw-propelled vessel.

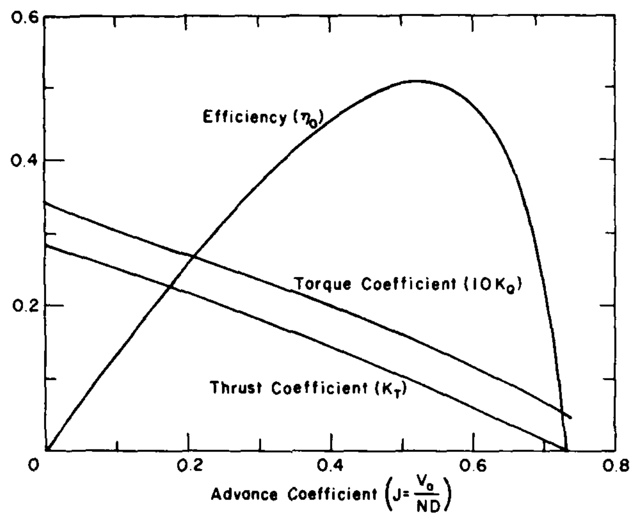

Figure 28. Open water characteristics of propeller 4665 (model of Katmai Bay propeller) test 2, January 1975 (from West 1975), where: T = *propeller thrust,* Q = *propeller torque,* $K_T = T/(\varrho n^2D^4)$, $K_Q = Q/(\varrho N^2D^5)$, $J = V_a/(ND)$, $\eta_o = TV_a/(2\pi QN)$, N = *revolutions/sec,* D = *propeller diameter.*

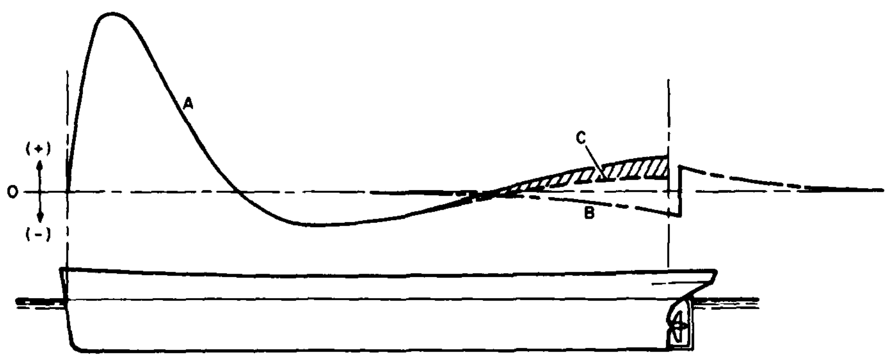

Figure 29. Pressure (total lead) distribution at stern of screw-propelled vessel.

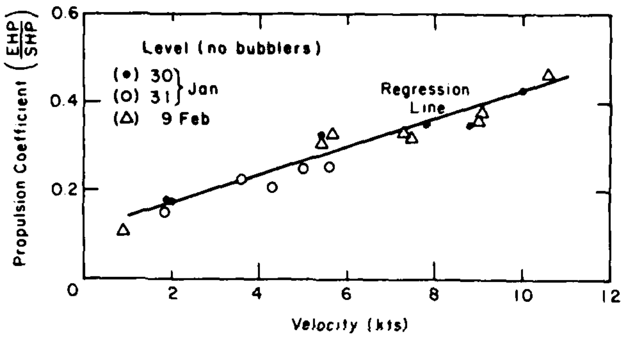

Figure 30. PC vs velocity for level plate ice with no bubblers operating.

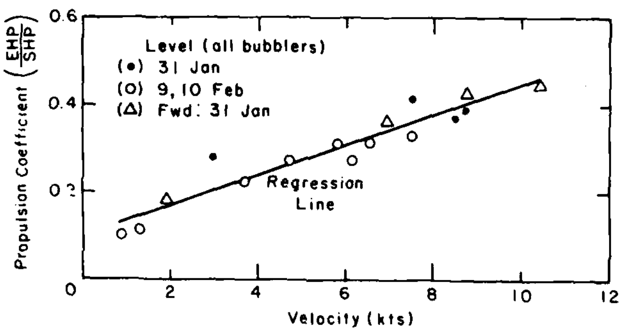

Figure 31. PC vs velocity for level plate ice with all bubblers operating.

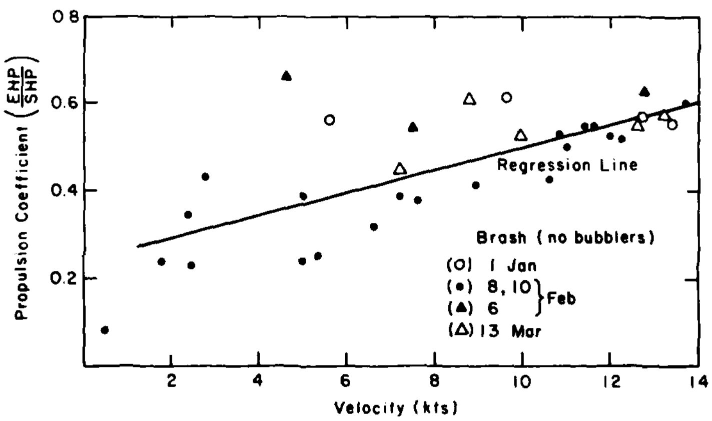

Figure 32. PC vs velocity in brash ice with no bubblers operating.

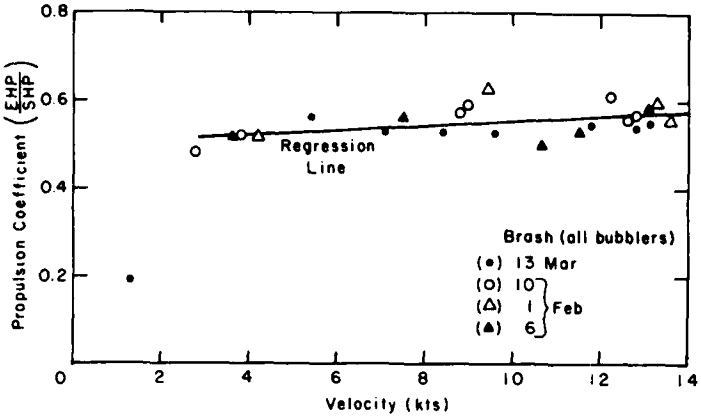

Figure 33. PC vs velocity in brash ice with all bubblers operating.

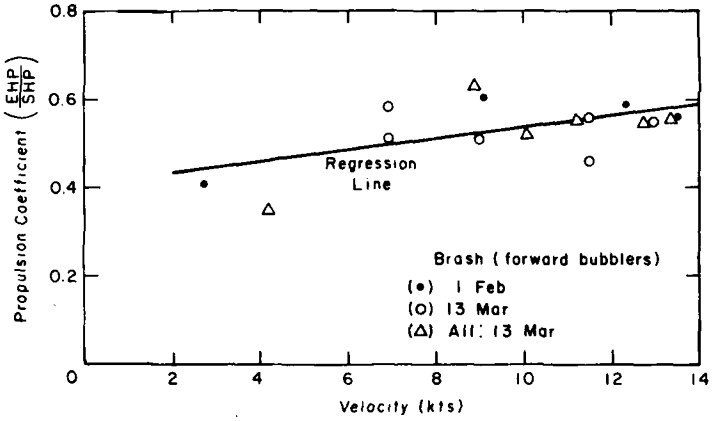

Figure 34. PC vs velocity in brash ice with only forward bubblers operating.

value of *t*. Computations of the *PC* using various values of *t* were made and are presented in Internal Report 621. The plots in Figures 31 to 34 were derived using a value of 0.2 for *t*.

Figures 30 and 31 represent the plot of the *PC* in level ice with and without the bubbler system in operation. There is very little difference between the two plots. The *PC* does not approach the ice-free water value of 0.565 but starts at 0.45 and drops to 0.12 with a decrease in speed.

It is apparent that some mechanism is affecting the *PC* in ice and decreasing the efficiency of the propulsion system. From the data collected in these tests, it is impossible to isolate the cause of the decrease in *PC*. However, one can speculate that it could stem from several causes:

1. An increase in *t* that would lead to a decrease in the available thrust and decreased *PC* as shown in Internal Report 621.

2. A decrease in *w* that would lead to a lower hull efficiency, thereby decreasing *PC*.

3. A decrease in the relative rotative efficiency by disturbances of flow pattern by the ice blocks.

4. A decrease in the propeller efficiency caused by one or a combination of the following effects: 1) disruption of the pressure field around the propeller blades by the ice blocks causing a

failure of the airfoil effect producing the thrust, 2) a larger amount of energy required to accelerate the ice blocks and water mixture compared to that needed for ice-free water, and 3) a loading up of the propeller such that it is not operating at its maximum efficiency, i.e. it is operating at a lower advance coefficient [$J = V_a/(nD)$, Fig. 28]. In order to isolate the cause for the decreased PC and effect design changes that would improve the efficiency further, more detailed tests are required.

Figure 32 is a plot for brash ice without the bubbler systems operational. The trend is similar to that of the previous two figures; however, the PC values are higher than those of the two previous plots, varying from 0.6 at 10 knots to 0.3 at 2 knots. The scatter of the data is greater due to the variation in ice conditions. It is evident that less ice is getting to the propeller area in this case.

Figures 33 and 34 show the extraordinary effect of the bubbler system. It appears that, with all the bubblers operating, the PC remains very close to the ice-free water value of 0.565. Figure 33 shows the PC in various thicknesses of brash ice with the bubblers in operation, during which it varied from 0.57 at 13 knots and 0.50 at 3 knots. Figure 33 shows the same trend with only the forward bubbler system activated.

It appears that the bubbler system is not only reducing the dynamic coefficient of friction between the ice and hull but is also, in brash ice, moving the ice blocks out of the slip stream of the propeller. The increase in PC from 0.32 to 0.52 at 3 knots is a phenomenon that deserves more detailed investigation. It appears the blocks of ice encountered in level ice-breaking are too large to be affected by the bubbler system. Therefore, the phenomenon observed in brash ice is not observed in plate ice.

Regression analysis

In order to obtain a predictor equation for the resistance of the *Katmai Bay*, the resistance data computed in Internal Report 621 for a thrust deduction factor t of 0.2 were utilized in a linear multiple regression program. The data were divided into four basic groups:

1. Level plate ice with no bubblers (LNB)
2. Level plate ice with bubblers (LAB)
3. Brash ice with no bubbler (BNB)
4. Brash ice with bubblers (BAB).

An attempt to refine the data to reflect the utilization of the forward and aft bubblers was made, however, there were insufficient data for regression analysis for the various configurations. Therefore, all three bubbler runs were considered as one grouping.

Past efforts by Vance (1974), Enkvist (1972) and others have indicated that the resistance of a vessel progressing through level ice can be broken down into three basic resistance components: one attributed to the breaking of the ice sheet, one attributed to submergence of the ice sheet and one attributed to the inertial (velocity) effects. The exact form of the resistance equation has been debated among the various researchers. The following regression equations contain independent variables that reflect the most feasible forms, i.e. V, V^2 σV. The equations used to predict the resistance in brash ice do not contain the ice strength related term.

It was evident after considerable analysis that one equation would not satisfy the total range of thicknesses obtained in brash ice. Tests were conducted in basically two thicknesses of brash ice, 18 to 22 in. and 40 to 50 in. It appears that in thinner brash ice there is considerably more energy expended in the inertia-related phenomenon, while in the thicker brash ice the submergence phenomenon dominates.

A regression analysis of the data was performed utilizing the following resistance equation (Vance 1974) for level ice:

$$R = C_0 \varrho_\Delta G B H^2 + C_1 \sigma B H + C_2 \varrho V^2 L H^{0.65} B^{0.35}$$
$$+ C_3 V \varrho_\Delta G^{0.5} H^{1.5} B + C_4 \sigma V G^{-0.5} H^{0.5} B$$
$$+ C_5 V^2 \varrho_\Delta H B \qquad (10)$$

where R = ice resistance of the vessel
G = acceleration of gravity
B = beam of the vessel at the water line
H = thickness of ice
σ = flexural strength of the ice
V = velocity of the vessel
ϱ_i = density of the ice
ϱ_Δ = difference in density between ice and water.

The equation was normalized for the regression program as follows:

$$R/(\varrho_\Delta G B H^2) = C_0 + C_1[\sigma/(\varrho_\Delta G H)]$$
$$+ (C_2 \varrho_i V^2 L)/(\varrho_\Delta G B^{0.65} H^{1.35})$$

$$+ C_3(V/\sqrt{GH})] + C_4[\sigma V/(\varrho_A G^{1.5} H^{1.5})]$$

$$+ C_5[V^2/(GH)] \qquad (11)$$

At the 95% significance level all terms except those associated with C_0 and C_1 were rejected. Therefore the final equation for resistance in level ice takes the form:

$$R = 55.8583\varrho_A GBH^2 + 0.0188\sigma VG^{-0.5}H^{0.5}B \qquad (12)$$

with a correlation coefficient of 0.91.

The equation for level ice with the bubblers operating takes the same form but with less emphasis on the submergence term:

$$R = 46.7937\varrho_A GBH^2 + 0.0208\sigma VG^{-0.5}H^{0.5}B. \qquad (13)$$

Figures 35 and 36 are plots of the above equations for ice thicknesses varying from 6 to 48 in. Superimposed on the plots are points from various full-scale runs.

The brash data were also analyzed using regression techniques with the following resistance equation:

$$R = C_0\varrho_A GBH^2 + C_1\varrho_A V^2LB^{0.35}H^{0.65}$$

$$+ C_2V\varrho_A G^{0.5}H^{1.5}B + C_3V^2\varrho_A HB \qquad (14)$$

and were normalized as follows:

$$R/(\varrho_A GBH^2) = C_0 + C_1V^2L/(\varrho_A GB^{0.65}H^{1.35})$$

$$+ C_2V/\sqrt{GH} + C_3V^2/GH. \qquad (15)$$

The only terms retained at the 95% significance level were those associated with C_0 and C_1, such that the equation for resistance in 18 in. of brash ice takes the form:

$$R = 0.1209\varrho_A GBH^2$$

$$+ 0.0622\varrho_A V^2LB^{0.35}H^{0.65} \qquad (16)$$

For 48 in. of brash ice the equation takes the form:

$$R = 4.4121\varrho_A GBH^2$$

$$+ 0.0306\varrho_A V^2LB^{0.35}H^{0.65} \qquad (17)$$

With the bubbler system in operation, the resistance predictors take the form:

$$R = 0.566\varrho_A GBH^2 + 0.055\varrho_A V^2LB^{0.35}H^{0.65} \qquad (18)$$

for 18 in. of ice, and

$$R = 4.011\varrho_A GBH^2 + 0.0278\varrho_A V^2LB^{0.35}H^{0.65} \qquad (19)$$

for 48 in. of ice.

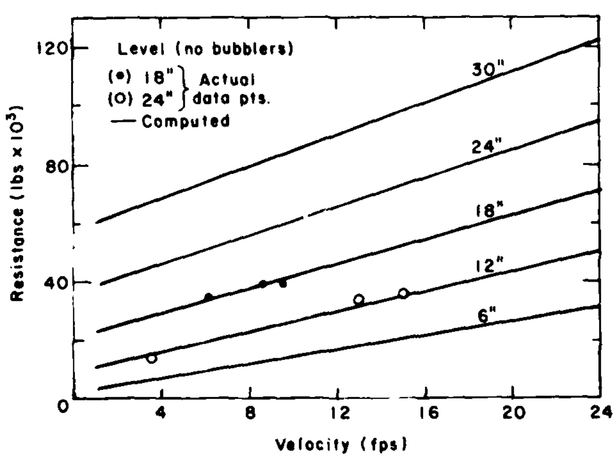

Figure 35. Level ice resistance with no bubblers operating.

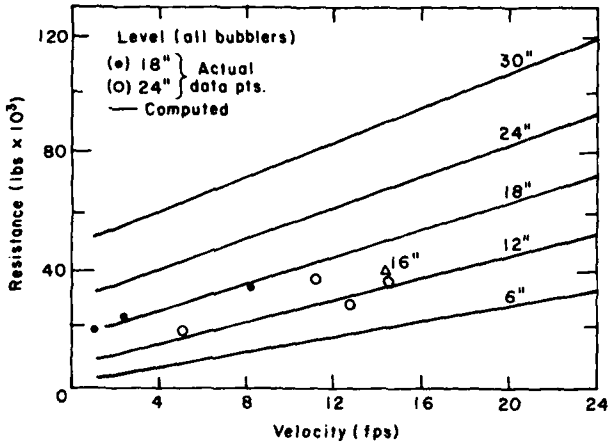

Figure 36. Level ice resistance with all bubblers operating.

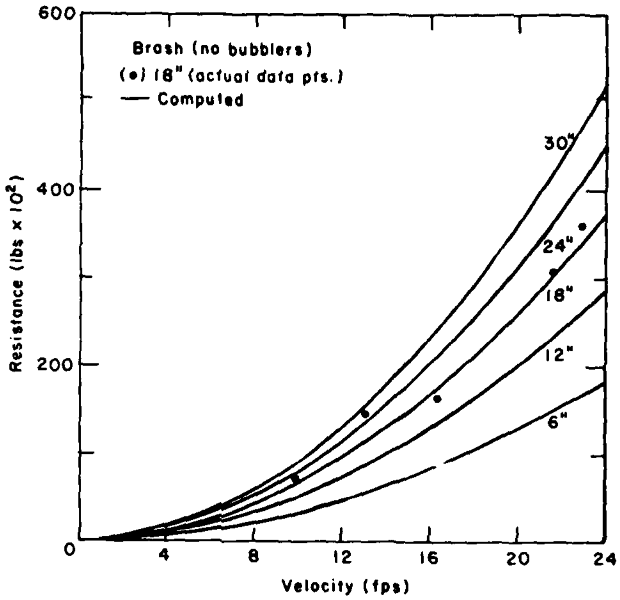

Figure 37. Ice resistance in 18 to 22 in. of brash ice with no bubblers operating.

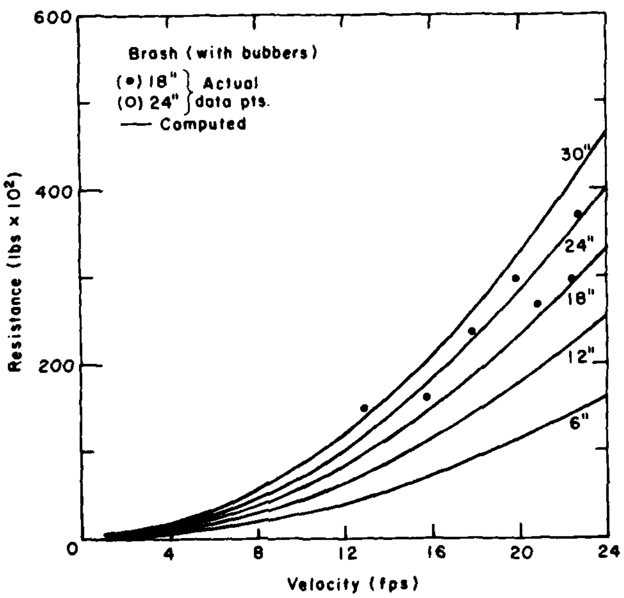

Figure 38. Ice resistance in 18 to 22 in. of brash ice with all bubblers operating.

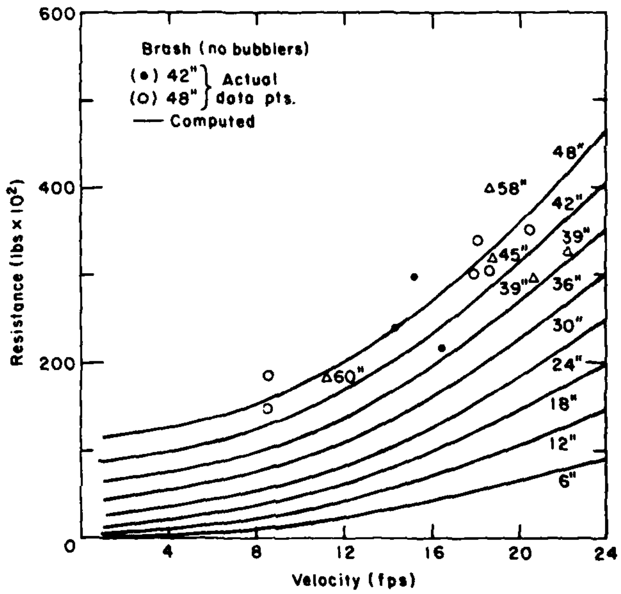

Figure 39. Ice resistance in 40 to 50 in. of brash ice with no bubblers operating.

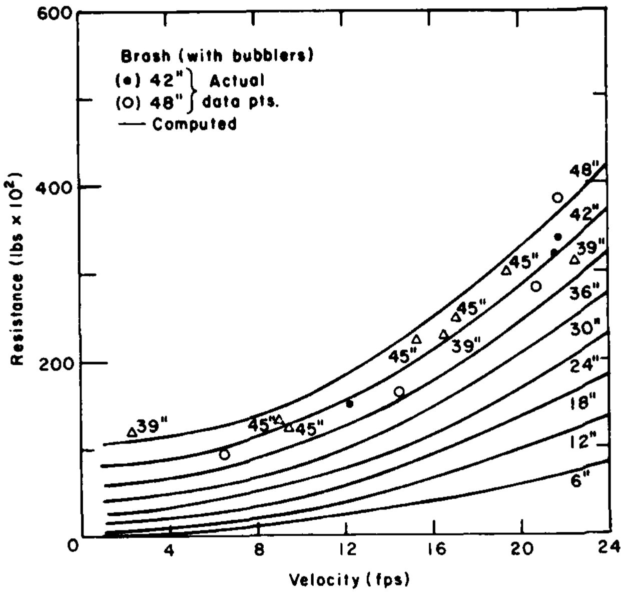

Figure 40. Ice resistance in 40 to 50 in. of brash ice with all bubblers operating.

Table 10. Comparison of brash ice power.

Run	*Ice thick (in.)*	*Ship vel (kt)*	*SHP*	*Bubbler*
3120	~ 18	12.75	2025	off
3730	~ 39	12.60	1985	off
3130	~ 18	13.70	2622	off
3740	~ 39	13.20	2297	off
4130	~ 16	13.60	2719	off
4400	~ 48	12.8	2590	all on
4030	~ 22	13.50	2740	all on
4740	~ 39	13.10	2263	all on

Due to the lack of detailed documentation of the brash ice runs early in the test period in the Whitefish Bay ship channel, anomalies appear in the data to the effect that several test runs indicate lower horsepower requirements for transiting the 48-in. ice than for transiting the thinner ice. Several examples from Internal Report 621 are given in Table 10.

These apparent disparities all occurred at the higher speed levels. It is difficult, at this stage, to determine the cause of these anomalies. Of course, the anomalies affect the regression equations and at high speeds the regression equation reflects the same anomalies.

Figures 37-40 are plots of the regression equations for brash ice resistance for large and small ice thicknesses and with the bubblers on and off. Superimposed on the plots are points from the full-scale tests.

CONCLUSIONS AND RECOMMENDATIONS

The tests conducted and described in this report have shown that the *Katmai Bay* can penetrate 22 in. of snow-covered plate ice in a continuous fashion and can ram through up to 30 in. of solid snow-covered plate ice. Limited testing indicated the vessel can penetrate unconsolidated pressure ridges up to 5 ft thick. Unfortunately, no pressure ridges of significant consolidation or size to stop the vessel were encountered. Use of the bubbler system reduced the power required some 25 to 35% in level ice.

The vessel displayed a capability of penetrating brash ice up to 4 ft thick in the shipping channel. Use of the bubbler system decreased the required power some 30 to 50%. In addition to lubricating the hull surface and decreasing the dynamic coefficient of friction between the ice and the hull, it appears that the bubblers are effective in increasing the propulsive coefficient in brash ice. A corresponding phenomenon was not observed in level ice.

The vessel rammed hard lake ice at up to 13 knots and no observable damage to the hull was noted. Detailed strain gauge readings were taken by NSRDC and are available in a separate NSRDC report still in preparation. The ramming tests indicated that the vessel was capable of reaching an impact velocity of 13 knots in about three ship lengths in an ice-clogged channel. Any further acceleration distance contributed little to the impact velocity. The ramming tests also indicated a relationship between ice thickness, impact velocity and the distance the vessel could penetrate the ice. The bubbler system appeared to be of little use in the ramming mode.

Although the tests met the primary objectives of evaluating the operational performance of the *Katmai Bay*, they also revealed many questions that could not be answered on the basis of the data collected. Insufficient data were collected to distinguish the relative effectiveness of

the forward and aft bubbler systems. Due to lack of documentation of the brash ice condition during the early ad-hoc brash ice tests, there appears to be an anomaly in the power required to transit thin and thick brash ice at high speeds. The latter, well-documented brash ice tests should be considered the more reliable.

Regression techniques were utilized to obtain predictor equations for the vessel resistance in level and brash ice with and without the bubbler system. These equations should be used with caution for they apply only to *Katmai Bay* class vessels within the limits of the test parameters measured.

Based on the results of these tests, there are several recommendations for further research that can be made. These recommendations fall into several categories.

Friction Factors. It is recommended that further tests be conducted utilizing the techniques used in these tests to refine the relationship between roughness and the coefficient of dynamic friction and the effect of velocity on the coefficient of friction.

Ice Properties. It is recommended that further efforts be made to characterize brash ice in both full scale and model scale. These efforts should include, but not be limited to, techniques to measure the thickness of the brash, the coverage of the brash, and, most importantly, the consolidation of the brash.

Ship Performance. It is recommended that further model tests be conducted to determine the nature of the loss of propulsion efficiency in ice. These tests should include propeller efficiency and self-propelled tests in ice-clogged water to determine the thrust deduction factor and the wake factor.

Bubbler System. More tests are necessary to determine the effectiveness of the bubbler system operating in various configurations. In addition it appears that a somewhat less powerful system may be just as effective. Both Schwarz (1978) and Wartsila Shipyard (1977) have indicated that bubbler systems can be effective with as little as 3 to 5% of the power of the main engine. More research should be undertaken to determine the effect of the bubbler system on the propulsion coefficiency.

Performance Prediction. Although the results obtained here will be compared to the various performance prediction techniques (i.e. model tests, analytical predictions and semi-empirical techniques) it will be difficult to make a direct comparison due to the absence of self-propelled model test data and a better understanding of the effect of ice on the propulsive coefficient.

Despite the shortcomings mentioned here, the tests conducted on the *Katmai Bay* are among the best-documented full-scale tests ever conducted on an icebreaking vessel and will make a significant contribution to the state of the art of icebreaker design.

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TABLES

CONVERSION FACTORS: U.S. CUSTOMARY TO METRIC (SI) UNITS OF MEASUREMENT

These conversion factors include all the significant digits given in the conversion tables in the ASTM *Metric Practice Guide* (E 380), which has been approved for use by the Department of Defense. Converted values should be rounded to have the same precision as the original (see E 380).

Multiply	*By*	*To obtain*
microinch	0.0254*	micrometer
inch	25.4*	millimeter
foot	0.3048*	meter
yard	0.9144*	meter
knot	0.5144444	meter/second
horsepower	745.6999	watt
pound-force/foot^2	47.88026	pascal
degree Fahrenheit	$t_{°C} = (t_{°F} - 32)/1.8$	degree Celsius

*Exact

A facsimile catalog card in Library of Congress MARC format is reproduced below.

Vance, George P.
Analysis of the performance of a 140-foot Great Lakes icebreaker: USCGC Katmai Bay / by George P. Vance. Hanover, N.H.: U.S. Cold Regions Research and Engineering Laboratory; Springfield, Va.: available from National Technical Information Service, 1980.
vi, 33 p., illus.; 28 cm. (CRREL Report 80-8.)
Prepared for U.S. Coast Guard under MIPR 270099-9-91769-9B, by U.S. Army Cold Regions Research and Engineering Laboratory.
Bibliography: p. 28.
1. Field tests. 2. Icebreakers. 3. Ice resistance. 4. Low friction coating. 5. Ship bubblers. I. United States. Army. Corps of Engineers. II. Army Cold Regions Research and Engineering Laboratory, Hanover, N.H. III. Series: CRREL Report 80-8.

☆U.S. GOVERNMENT PRINTING OFFICE: 1980—600-408/426